# AN EXPERIMENT IN USING INTERACTIVE COMPUTER GRAPHICS IN TEACHING TRANSIENT TRANSMISSION-LINE THEORY

by

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# INTRODUCTION

An interactive computer graphics routine was developed and used in teaching EE 553, Electromagnetic Fields, autumn quarter, 1969, in the Electrical Engineering Department of the University of Utah. The routine displayed the propagation of the voltage waveform produced by a step-function generator down a two-wire transmission line, showing reflections for the user's choice of various values of resistance, capacitance, or inductance at the end of the line and for various values of generator resistance. This report describes the development and use of the system.

## WHY COMPUTER GRAPHICS IN TEACHING AND HOW?

The computer is a simulator which can be used to simulate quantities it is not possible to see, such as the voltage wave propagating down a transmission line. In conjunction with the graphics display, this simulation can be extremely valuable to someone trying to learn concepts because it allows him to visualize abstract quantities. The interactive properties of a computer graphics system are extremely valuable because they allow the user to quickly gain qualitative understanding by varying parameters and noting the change in behavior. This allows him to obtain valuable insight into the behavior of the system he is studying. Thus the simulation of the computer in combination with the graphics display can be a powerful learning tool. Without the graphics display, the user would have great difficulty in observing qualitative behavior, and he would have to work much harder and longer to get his insight.

In an attempt to optimize a graphics system for learning about transients on transmission lines, I tried to design the system according to five principles which I believe summarize the requirements for good learning. They are:

1. The learner must be active
2. Feedback must be provided. The learner must be able to tell when he is right and wrong; right choices should be reinforced.
3. Some kind of reward or sense of accomplishment or satisfaction must be provided.

4. The learner must be allowed to progress at his own speed. Otherwise the slow learner will be frustrated and confused, and the faster learner will be bored.
5. The learner must be motivated, either by self-motivation or by stimulation by someone else.

# A DESCRIPTION OF THE GRAPHICS ROUTINE

The graphics routine simulates the system shown in Figure 1. The user types in on the teletype the normalized values of generator resistance RG, and one normalized value of either a resistance, an inductance, or a capacitance at the end of the line. Then the voltage waveform is shown as it propagates down the line, hits the element at the end, is reflected, travels to the generator, is reflected, and then travels to the other end. That is as much of the wave propagation as the routine shows. A typical display is shown in Figure 2.

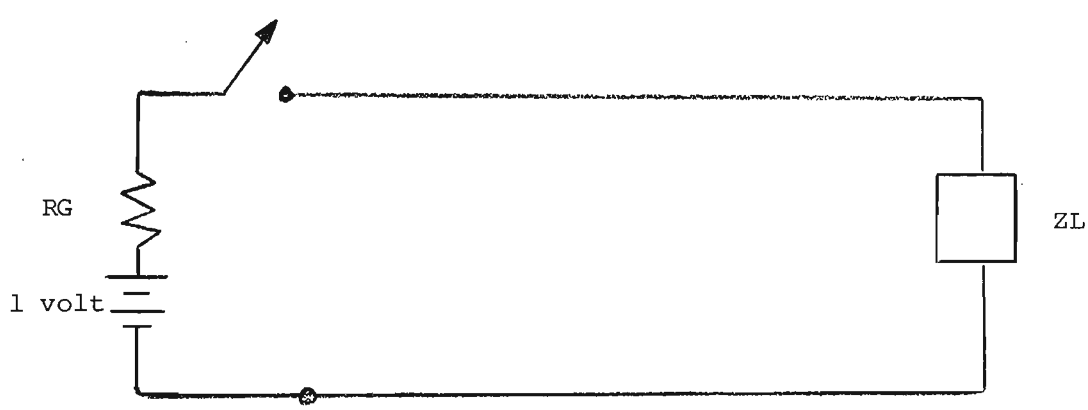


Figure 1: The system simulated by the graphics routine.

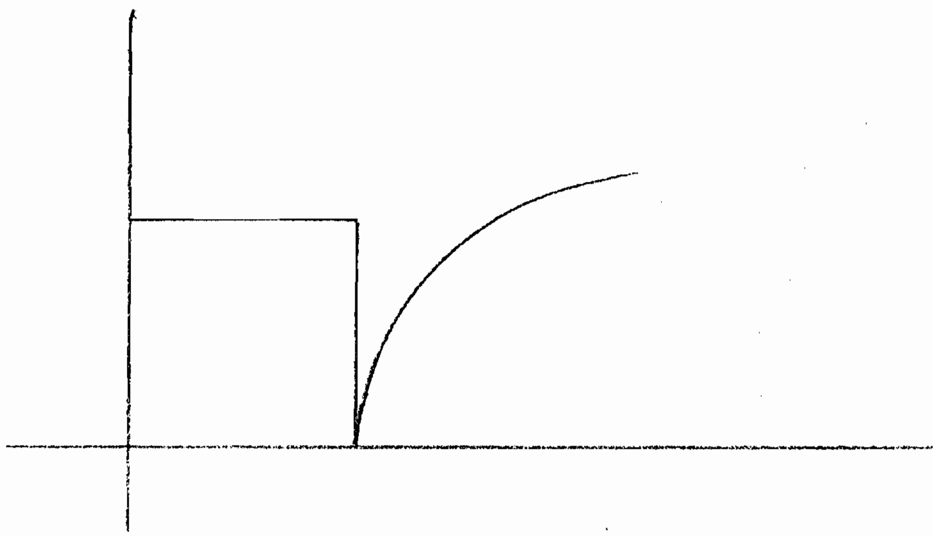

Figure 2: A typical display. The ordinate is voltage, the abscissa is positioned along the transmission line. This picture is for a capacitor at the end of the line, and the wave has traveled down to the capacitor and has been reflected back. As time progresses, the notch moves to the left.

The routine is programmed so that the wavefront propagates to the middle of the line and then time is stopped so the waveform becomes stationary. This is to allow the student to study the waveform. Then the student types GO and the wave progresses down to the end of the line, is reflected, and stops again at the midpoint until the student types GO, etc. This allows the student to see how the waveform propagates, but it also gives him a chance to sketch the waveform.

Since the first requirement for good learning listed previously is that the learner must be active, I prepared a set of questions for the student to answer by using the graphics routine. Some of the questions were to be answered before the student used the graphics routine; others were to be answered while he was using the routine. The questions were designed to make a student seek answers from the graphics system. In this way he is not simply watching the display, but is trying various parameters in order to understand what happens and why. The set of questions along with some instructions for using the system are included in Appendix A. The instructions summarize the system, and they include a simplified flow diagram.

The program listing is given in appendix B. The computer graphics system used was a graphics system of the Computer Sciences Division at the University of Utah.[1] The computing was done on a Univac 1108, and the display was on an IDI display scope.

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[1] Lee Copeland and C. Stephen Carr, "GS-Graphics System", Technical Report 4-1, Computer Science, University of Utah, Salt Lake City, Utah, November 15, 1967.

## RESULTS OBTAINED

I had 17 students in the class. They used the graphics routine in groups of two or three; each group spent about an hour. Since the system swapped out when the wave was not propagating, only a very small part of the hour was used in computing time. The average 1108 computer time used by one group was about 275 seconds. Although I did not attempt a quantitative measurement of whether the students learned more or faster than they would have without the graphics routine, it was very apparent to me that they did learn both more and faster. They were very enthusiastic and felt that they benefited greatly by using the system. Before using it I did not have a good qualitative understanding of what the waveforms would be like. I could get the mathematical expression and predict the waveform from that, but I did not have a good qualitative feel for what would happen. From using the system, I came to this qualitative picture: a capacitator initially looks like a short circuit and finally looks like an open circuit. Hence when the wavefront first reaches a capacitor at the end of the line it is reflected as it would be by an open circuit. Since a short circuit forces the voltage to zero and an open circuit doubles the voltage, a capacitor produces a waveform that looks like that in Figure 3. The point where V(z) = 0 corresponds to the point where the capacitor looked like a short circuit. Then the capacitor started charging and the reflected wave started to increase. The exponential increase is going toward twice the incident voltage, which is what would be produced by an open circuit. How long the capacitor

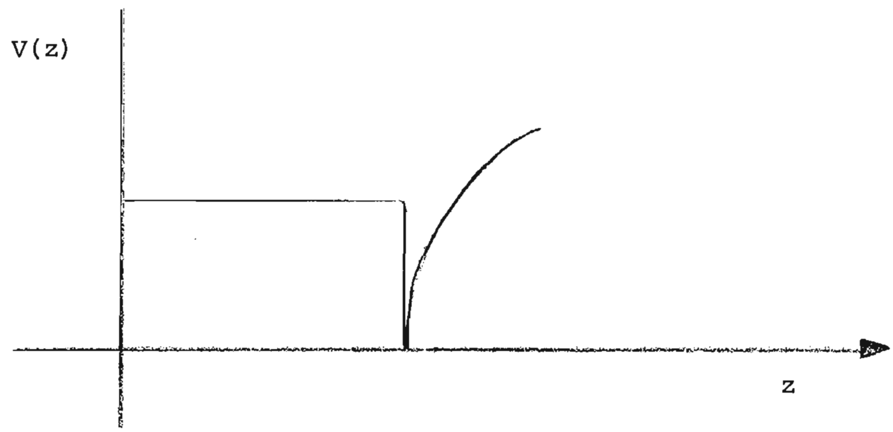


Figure 3: A qualitative picture of the waveform caused by a capacitor at the end of the line.

takes to go from a short circuit to an open circuit depends on how large the capacitor is. From this kind of picture, the qualitative nature of the waves can be easily described. A similar picture holds for an inductor on the end of the line, but an inductor initially looks like an open circuit and finally like a short circuit. Hence an inductor produces a waveform like that shown in Figure 4.

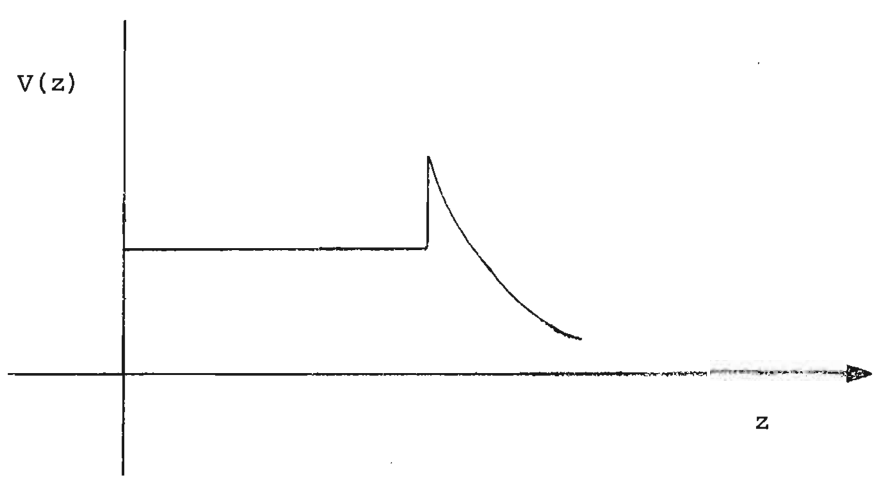


Figure 4: A qualitative picture of the waveform produced by an inductor on the end of the line.

First the voltage doubles, and then it goes to zero. Also, when the wave first leaves the generator, its magnitude is determined by the voltage divider formed by the characteristic impedance of the line and the generator impedance, regardless of what is on the other end of the line. This is true because, when the wave starts out, the line looks infinitely long; hence the wave sees an impedance equal to the characteristic impedance. It does not know what is at the end of the line until it gets there.

I have given only some of the details of the qualitative picture I gained from using the graphics system, but I can qualitatively describe the various waveforms produced by resistance, inductance, or capacitance on the end of the line. Furthermore, I can do the same when a pulse generator, rather than a step function generator, is used - and the students could do the same. I probably could have come to the same understanding without the graphics system, but it would have taken me much longer to do so. I am convinced by my own learning experience that this system is a tremendous learning tool.

## CONCLUSIONS

I feel that this experiment was very valuable and successful. The graphics system provided both me and my students with insight and understanding that I think we might not have gained otherwise, at least not nearly as fast. Furthermore, I think that this is only a small indication of the potential usefulness of interactive graphics systems as learning tools. I believe the possibilities of exciting uses for interactive computer graphics in our education system are endless.

# APPENDIX A

This appendix contains a set of questions and a description of the graphics routine, both of which were given to the students in the class. Some of the questions were to be answered before using the graphics routine, while others were to be answered during the use of the graphics routine.

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EE 553 QUESTIONS TO BE ANSWERED IN CONNECTION WITH THE GRAPHICS ROUTINE Autumn 1969

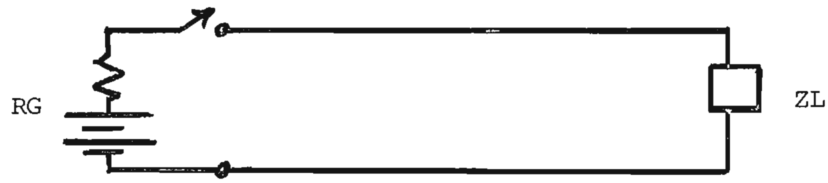


Fig. 1

1. In Fig. 1, when ZL = 0 (short circuit), does the voltage wave reflected by ZL add to or subtract from the voltage wave incident on ZL?

2. In Fig. 1, when ZL = ∞ (open circuit), does the voltage wave reflected by ZL add to or subtract from the voltage wave incident on ZL?

3. When ZL = R, does the voltage wave reflected by R add to or subtract from the incident voltage wave? Discuss the three cases R > 1, R < 1, R = 1. R is normalized to the characteristic impedance as in the language of the graphics program.

4. How does the value of RG affect the wave reflected from the generator? State how RG > 1, RG < 1, RG = 1, affect the wave reflected from the generator. Note that the wave incident on the generator is the wave reflected by ZL. RG is normalized.

5. Compare how R reflects waves with how RG reflects waves.

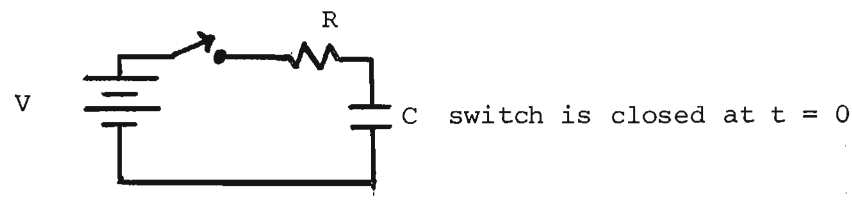


Fig. 2. Ordinary R-C circuit.

6. a. What is the voltage across the capacitor at t = 0 in the circuit shown in Fig. 2? Does C initially look like an open circuit or a short circuit?

   b. When ZL = C in Fig. 1, what would you expect the voltage across C to be when the voltage wave initially hits C? Does C initially look like an open circuit or a short circuit to the incident wave? How would you expect this to affect the reflected wave?

   c. Describe the nature of the reflected voltage wave.

   d. If the value of C is increased in the circuit of Fig. 2, does the voltage across C build up more rapidly or less rapidly with time?

   e. How would you expect that increasing the C on the end of the transmission line would affect the reflected wave?

   f. Describe how increasing and decreasing C affects the reflected wave.

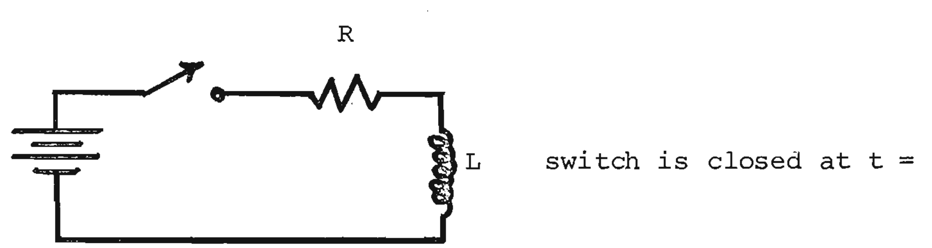


Fig. 3. Ordinary R-L circuit.

7. a. What is the voltage across the inductor at t = 0 in the circuit shown in Fig. 3? Does L initially look like an open circuit or a short circuit?

   b. When ZL = L in Fig. 1, what would you expect the voltage across L to be when the voltage wave initially hits L? Does L initially look like an open circuit or a short circuit to the incident wave? How would you expect this to affect the reflected wave?

   c. Describe the nature of the reflected voltage wave.

   d. If the value of L is increased in the circuit of Fig. 3, does the voltage across L build up more rapidly or less rapidly with time?

   e. How would you expect that increasing the L on the end of the transmission line would affect the reflected wave?

   f. Describe how increasing and decreasing L affects the reflected wave.

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EE 553 | INSTRUCTIONS FOR USING THE GRAPHICS ROUTINE SHOWING TRANSIENT WAVES ON TRANSMISSION LINES | Autumn 1969

1. Your instructor must be present to read in the deck and set up the system for you. A sign-up sheet for reserving time on the graphics system will be provided in class. The graphics routine is for use on the FORTRAN V INTERACTIVE GRAPHICAL SYSTEM using the Univac 1108 computer, the display scope, and the teletype console.
2. A simplified flow chart is attached. In order to keep the chart simple, some of the details have not been shown. These are given in comments below. The graphics routine displays the voltage wave on a transmission line produced by a step function generator. Values of generator resistance and load inductance, capacitance, or resistance can be chosen.
3. The definitions of the variables in the graphics program are:

   RG: normalized generator resistance

   L: normalized load inductance

   C: normalized load capacitance

   R: normalized load resistance

   The normalization of the parameters is given by:

$$L = \frac{L_L}{Z_o(\ell/v)}$$

$$C = \frac{Z_o C_L}{(\ell/v)}$$

$$R = \frac{R_L}{Z_o(\ell/v)}$$

$$RG = \frac{R_G}{Z_o(\ell/v)}$$

where $L_L$, $C_L$, $R_L$, $R_G$ are the load inductance, load capacitance, load resistance, generator resistance, respectively. $Z_o$ is the transmission line characteristic impedance, $\ell$ is the length of the transmission line, and v is the velocity of propagation along the line. Since $\ell$/v is the time it takes for the wave to travel the length of the line, the parameters are normalized to the characteristic impedance and the propagation time.

4. The program is written so that the graphics system is initialized and the axes are displayed on the scope. Then the program SWAPS OUT. This means that the 1108 computer returns to batch processing until appropriate instructions are typed on the teletype, at which time the system SWAPS IN and continues the graphics routine. What the system does when it SWAPS IN depends on what was typed on the teletype. For example, if L = 1.8 ⌧ is typed in, the system SWAPS IN, sends the first picture and SWAPS OUT. The symbol ⌧ stands for the key marked "carriage return" on the teletype keyboard. The picture shows the voltage wave which would travel down a transmission line with an inductive load impedance at the end of the line. The wave progresses to the midpoint of the line, and

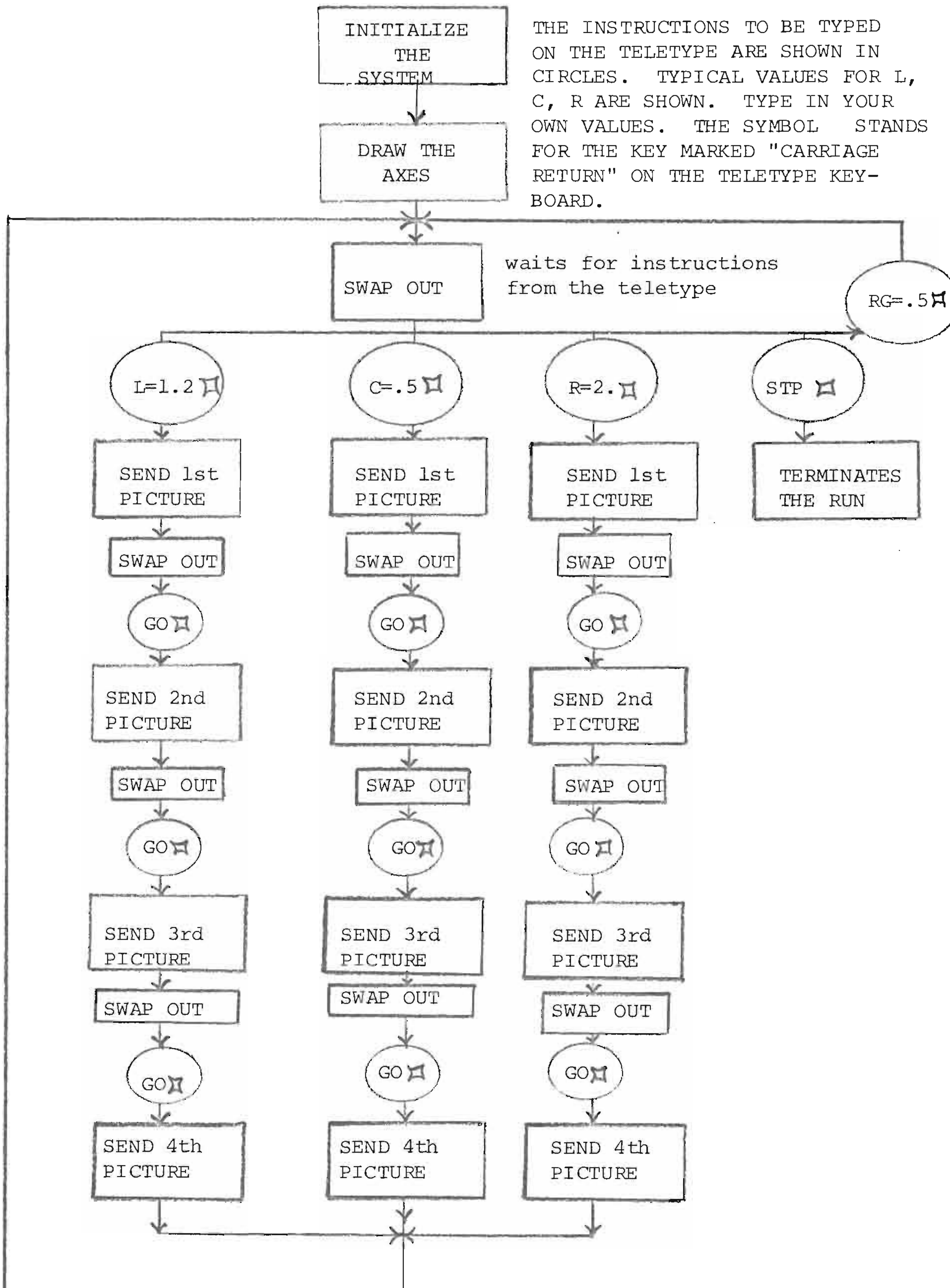
then time is stopped so the user can study the waveform. When he is ready, the user then types GO ⌑ and the wave progresses to the end of the line, is reflected, progresses back to the midpoint where time is again stopped so the user can again study the waveform. The process is then repeated until four pictures have been shown. The program is limited to only two reflections of the wave. That is, the wave travels the length of the transmission line three times. Of course, on a real transmission line, the waves continue to propagate and be reflected, but the graphics simulation is limited to two reflections for obvious economical reasons.

5. If a value of RG is typed in, the value is stored, but the system SWAPS OUT and no picture is displayed. A value of L, C, or R must be typed in before a picture is displayed. If a value of L, C, or R is typed in before a value of RG, the appropriate picture will be displayed with RG = .5
6. If an error is made in typing, type ⌑. The teletype will then Underline the error with *, type >, and wait for the correct statement to be typed in.
7. If GO ⌑ is typed after the last picture, the first picture will be displayed again, with whatever parameters were used last. That is, the system will return to the beginning of the sequence it just completed.
8. If a value of L, C, or R is typed in after <u>any</u> picture, the sequence will start over using the new value typed in. For example, if L = 1.3 was typed in, the first picture displayed, and then R = 1.8 ⌑ was typed

in, the system would next display the first picture in the R sequence. Then typing GO ⌘ would show the second picture in the R sequence, etc. Hence you can jump from any point in one sequence to the beginning of any sequence. You cannot jump to a point other than the beginning of a sequence.

9. An IN OUT message is displayed in the lower left-hand corner of the scope to show the status of the SWAP. Sometimes it takes a few seconds after the IN message is displayed for the SWAP IN to actually occur.
10. The generator voltage is 1. Dots occur on the voltage axis at 1 unit and 2 units.
11. The run is terminated by typing STP ⌘. Then the deck must be run again before any further use of the system can be made.
12. In order to use the system economically, you must be well prepared. Study the instructions carefully and plan beforehand what values of the parameters you plan to use. You will be given ample opportunity to ask questions about the system before you actually use it.

SIMPLIFIED FLOW CHART FOR THE GRAPHICS ROUTINE



# APPENDIX B

This appendix contains the program listing for the graphics routine.

```
@ELT,DIL DURNEY
ELT PROCESSOR LEVEL       3
          000          REAL L
          000          INTEGER V2(155),DF(800)
          000          NAMELIST/WAVE/R,L,C,STP,GO,RG
          000          CALL RELOAD
          000          CALL INOUTM
          000          CALL SETLST
          000          READ(5,WAVE)
          000          CALL JUMPS('WAVE',$10,$30,$31,$70,$75)
          000          CALL SWPCHR('¤')
          000          RG=.5
          000          L=1.
          000          C=1.
          000          R=2.
          000          IN=5
          000          CALL SETDF(DF,I)
          000          CALL ORG(200,400)
          000          CALL POS(300,0)
          000          CALL VEC(0,0)
          000          CALL VEC(0,250)
          000          CALL DOT(0,120)
          000          CALL DOT(0,240)
          000          I1=I
          000          CALL SENDF
          000       80 CALL SWAP
          000          CALL TTY
          000          GO TO 30
          000       75 GO TO(102,103,104,101,80),IN
          000       10 RHOL=(R-1.)/(R+1.)
          000          KL=1
          000          GO TO 40
          000       30 S=1.
          000          TAU=L
          000          KL=2
          000          GO TO 32
          000       31 S=-1.
          000          TAU=C
```

```
      KL=2
   32 AA=120.*S/(1.+RG)
      A=1./(300.*TAU)
      V2(1)=AA
      DO 33 J=2,152
      B=J
   33 V2(J)=AA*(-1.+2.*EXP(-(4.*B-4.)*A))
   40 RHOG=(RG-1.)/(RG+1.)
      IY=120./(1.+RG)
  101 DO 41 N=4,152,4
      I=I1
      CALL POS(0,IY)
      DO 42 K=4,N,4
   42 CALL VEC(K,IY)
      CALL VEC(N,0)
      N4=N+4
      DO 43 K=N4,300,4
   43 CALL VEC(K,0)
   41 CALL SENDF
      IN=1
      CALL SCHAR
      CALL WRITAT(100,-100,'FIRST PICTUREΔ')
      CALL SENDF
      CALL SWAP
      CALL TTY
  102 DO 44 N=156,300,4
      I=I1
      CALL POS(0,IY)
      DO 45 K=4,N,4
   45 CALL VEC(K,IY)
      CALL VEC(N,0)
      IF(N.EQ.300)GO TO 44
      N4=N+4
      DO 46 K=N4,300,4
   46 CALL VEC(K,0)
   44 CALL SENDF
      IY=120.*(RHOL+1.)/(1.+RG)
      IY1=120./(1.+RG)
      DO 50 N=4,152,4
      I=I1
      N4=N/4
      NN=N4+1
      IF(KL.EQ.2)IY=V2(NN)+IY1
      CALL POS(300,IY)
      DO 51 K=1,N4
      IF(KL.EQ.2)IY=V2(NN-K)+IY1
   51 CALL VEC(300-4*K,IY)
      CALL VEC(300-N,IY1)
      N4=N+4
      DO 52 K=N4,300,4
   52 CALL VEC(300-K,IY1)
   50 CALL SENDF
      IN=2
      CALL WRITAT(100,-100,'SECOND PICTURE Δ')
      CALL SENDF
```

```
000          CALL SWAP
000          CALL TTY
000      103 DO 53 N=156,300,4
000          I=I1
000          N4=N/4
000          NN=N4+1
000          IF(KL.EQ.2)IY=V2(NN)+IY1
000          CALL POS(300,IY)
000          DO 54 K=1,N4
000          IF(KL.EQ.2)IY=V2(NN-K)+IY1
000       54 CALL VEC(300-4*K,IY)
000          CALL VEC(300-N,IY1)
000          IF(N.EQ.300)GO TO 53
000          N4=N+4
000          DO 55 K=N4,300,4
000       55 CALL VEC(300-K,IY1)
000       53 CALL SENDF
000          IY2=120.*(RHOL+1.)/(1.+RG)
000          IY3=120.*RHOL*RHOG/(1.+RG)
000          IY=IY2+IY3
000          DO 60 N=4,152,4
000          I=I1
000          N4=N/4
000          NT=N4+76
000          IF(KL.EQ.2)IY2=V2(NT)+IY1
000          CALL POS(300,IY2)
000          KK=75-N4
000          DO 61 K=1,KK
000          IF(KL.EQ.2)IY2=V2(NT-K)+IY1
000       61 CALL VEC(300-4*K,IY2)
000          MM=N4+1
000          DO 62 M=1,MM
000          IF(KL.EQ.2)IY=RHOG*V2(M)+V2(2*N4+2-M)+IY1
000       62 CALL VEC(N+4-4*M,IY)
000       60 CALL SENDF
000          IN=3
000          CALL WRITAT(100,-100,'THIRD PICTURE Δ')
000          CALL SENDF
000          CALL SWAP
000          CALL TTY
000      104 DO 63 N=156,292,4
000          I=I1
000          N4=N/4
000          NT=N4+76
000          IF(KL.EQ.2)IY2=V2(NT)+IY1
000          CALL POS(300,IY2)
000          KK=75-N4
000          DO 64 K=1,KK
000          IF(KL.EQ.2)IY2=V2(NT-K)+IY1
000       64 CALL VEC(300-4*K,IY2)
000          MM=N4+1
000          DO 65 M=1,MM
000          IF(KL.EQ.2)IY=RHOG*V2(M)+V2(2*N4+2-M)+IY1
000       65 CALL VEC(N+4-4*M,IY)
```

```
000          63 CALL SENDF
000             IN=4
000             CALL WRITAT(100,-100,'LAST PICTURE Δ')
000             CALL SENDF
000             GO TO 80
000          70 CALL EXIT
000             END
```

@ FIN